

FISSION FRAGMENT SPECTROSCOPY ON A $^{28}\text{Si}+^{28}\text{Si}$ QUASI-MOLECULAR RESONANCE

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(November 2, 2013)

Abstract

Fragment-fragment- γ triple coincident measurements of the $^{28}\text{Si} + ^{28}\text{Si}$ reaction at $E_{\text{lab.}} = 111.6$ MeV carefully chosen to populate $J = 38^+$ resonance have been performed at the VIVITRON tandem facility by using Eurogam Phase II γ -ray spectrometer. In the $^{28}\text{Si} + ^{28}\text{Si}$ exit-channel, the resonance behavior of the $^{28}\text{Si} + ^{28}\text{Si}$ reaction at the beam energy is clearly confirmed. An unexpected spin disalignment has been observed in the measured angular distributions in the elastic, inelastic, and mutual excitation channels. This disalignment is found to be consistent with particle- γ angular correlations and supported by the molecular model prediction of a “butterfly motion”. The $K^\pi = 0_3^+$ band corresponding to the large prolate deformation of the ^{28}Si is more intensely fed in the resonance region. The selective population of high-excited states are discussed within a statistical fusion-fission model. In the $^{32}\text{S} + ^{24}\text{Mg}$ exit-channel, the spectroscopic study of the ^{32}S , has revealed the contribution of a new γ -ray transition $0^+(8507.8 \text{ keV}) \rightarrow 2_1^+(2230.2 \text{ keV})$.

PACS number(s): 25.70.Ef, 25.70.Jj, 25.70.Gh, 25.70.Lm, 24.60.Dr, 23.20.Lv

I. INTRODUCTION

The appearance of quasi-molecular resonances in light heavy-ion collisions such as $^{28}\text{Si} + ^{28}\text{Si}$ [1] or $^{24}\text{Mg} + ^{24}\text{Mg}$ [2] may open up the possibility for studying nuclear structure at high spin in the continuum of the combined complex. The large-angle yields in the elastic and inelastic scattering channels show correlated narrow-width resonant structures, which have been suggested to be associated with quasi-stable configurations with extreme deformation [3]. This interpretation is supported by Nilsson-Strutinsky model calculations of the potential energy surface, yielding high-spin prolate shape isomers in the ^{56}Ni - ^{48}Cr mass region [4,5] and by the recent discovery of a new region of the superdeformation for $A \simeq 60$ [6].

This very striking quasi-molecular resonant structure is possibly connected to a rather unusual subset of high-spin states stabilized against the mixing into the more numerous compound nucleus states by some special symmetry [3]. As a matter of fact recent theoretical investigations have indicated that shell-stabilized “hyperdeformed” shapes may exist in the ^{56}Ni nucleus with large angular momenta [5]. By the use of a molecular model proposed by Uegaki and Abe [7], a stable configuration of the dinuclear system is found to be an equator-equator touching one, due to the oblate deformed shape of the ^{28}Si nuclei [8,9]. In this paper, we present for the first time experimental results using very powerful coincidence techniques, which indicate the possible occurrence of a butterfly mode responsible for the quasi-molecular resonant structure and the search for highly deformed bands in the ^{28}Si nucleus produced in the $^{28}\text{Si} + ^{28}\text{Si}$ reaction at a resonance energy $E_{\text{lab}} = 111.6$ MeV.

II. EXPERIMENTAL PROCEDURES

The experiment was performed at the IReS Strasbourg VIVITRON tandem facility with a ^{28}Si beam at the bombarding energy $E_{\text{lab}}(^{28}\text{Si}) = 111.6$ MeV carefully chosen to populate the well known 38^+ resonance [10]. The ^{28}Si beam was used to bombard a $25\text{ }\mu\text{g}/\text{cm}^2$ thick ^{28}Si target. The thickness of the target corresponds to an energy loss of 130 keV smaller than the resonance width ($\Gamma_{c.m.} \approx 150$ keV). The experiment has been carried out in triple coincidence modes (fragment-fragment- γ). The fission fragments were detected in two pairs of large-area position-sensitive Si(surface-barrier) detectors placed on either side of the beam axis and their masses were determined by using standard kinematic coincidence techniques [11]. The γ -rays were detected in Eurogam Phase II multi-detector array [12], which consists of 54 Compton-suppressed germanium (Ge) detectors, 30 tapered coaxial Ge detectors from Eurogam Phase I located in the forward and backward hemispheres, and 24 clover detectors installed at $\sim 90^\circ$ relative to the beam axis. The number of the Ge crystals at each angle with respect to the beam direction is (5, 22°), (10, 46°), (24, 71°), (24, 80°), (24, 100°), (24, 109°) (10, 134°) and (5, 158°). Energy and relative efficiency calibrations of Eurogam Phase II were obtained with standard γ -ray sources and a AmBe source for the higher energy γ -ray region [12,13].

III. EXPERIMENTAL RESULTS

In order to better understand the experimental results, we present in the Fig.1 a two-dimensional energy spectrum E_3 - E_4 of the fragments in coincidence in the respective angular ranges $30.5^\circ \leq \theta_3^{\text{lab.}} \leq 56.4^\circ$ and $29.7^\circ \leq \theta_4^{\text{lab.}} \leq 58.4^\circ$. Three regions, noted 1, 2 and 3, can be easily distinguished in the figure. The region 1 corresponds to the binary products of the $^{28}\text{Si} + ^{28}\text{Si}$ reaction. In this region the spectrum shows well structured distributions indicating that the bombarding energy corresponds well to the resonance energy. The region 2 arises from the reaction products of the ^{28}Si with a contamination (^{63}Cu), and region 3 corresponds to the light charged particles (p , α) coincidences arising from the fusion-evaporation of the ^{56}Ni compound system. The selection of the different exit channels has been obtained by using mass spectra constructed by standard binary kinematic relations [12].

The γ -ray emitted by excited fragments are detected by the Ge detectors of Eurogam Phase II. Doppler-shift corrections were applied to the γ -ray data on an event-by-event basis using measured velocities of the detected fragments by using the following relativistic-like equation :

$$E_\gamma = E_0 \left(1 + \beta \cos \vartheta_D - \frac{1}{2} \beta^2 \right) \quad (1)$$

where $\cos \vartheta_D$ is Doppler angle. Since the velocities of the fission fragments ($\beta (^{28}\text{Si}) = \frac{v}{c} = 7.4 \%$) are larger than the velocities of the evaporation residues ($\beta = \frac{v}{c} = 2 \%$), then the equation (1) is well adapted for fusion-fission (FF) reactions.

A - Coincidence measurement for $^{28}\text{Si} + ^{28}\text{Si}$ exit channel

Reaction Q -value spectra were obtained for the different binary-reaction channels based on the known entrance-channel parameters, the deduced mass of the fragments, and the measured fragment angles. In Fig.2 the experimental excitation-energy (E_x) spectrum for $^{28}\text{Si} + ^{28}\text{Si}$ exit channel is displayed by points and the curves are for the calculations of

the transition state model (TSM) for fission decay. For E_x values less than 12 MeV the identification of the peaks is clear. Pronounced structures are still observed in this spectrum at high excitation energies. Since the number of possible mutual excitations becomes large above 12 MeV, the TSM calculations are in good agreement with the data and suggest the dominance of fission decay at high excitation energy. The disagreement for the low-lying states is due to the resonant behavior of this exit-channel.

The $^{28}\text{Si}(^{28}\text{Si}, ^{28}\text{Si})^{28}\text{Si}$ identical particle exit-channel at $E_{\text{lab.}} = 111.6$ MeV was found to have at backward angles (between $70^\circ \leq \theta_{c.m.} \leq 110^\circ$) strongly oscillatory angular distributions for the elastic, inelastic, and mutual excitation channels as shown in Fig.3. The present large-angle high-quality data, with good position-resolution and high statistics, are well described by the curves of Fig.3 as calculated by $[P_L(\cos \theta_{c.m.})]^2$ shapes with $L = 38$ \hbar in perfect agreement in the elastic channel with the previous data of Betts et al. [10]. The fact that the measured angular distributions in the elastic, inelastic, and mutual excitation channels correspond to shapes characterized by the same single Legendre polynomial squared means that the resonant behavior is dominated by a unique and pure partial wave associated with the angular momentum value $L = 38$ \hbar . This value can finally be considered as the spin of the well defined and isolated quasi-molecular resonance. The dominance of the angular momentum $L = 38$ \hbar in these three resonant channels implies that the projection of the spin along the direction perpendicular to the reaction plane is $m = 0$.

In order to understand this disalignment we will focus our analysis on the fragment-fragment- γ coincidence data of the $^{28}\text{Si} + ^{28}\text{Si}$ exit channel. Spin-alignment estimations of the low-lying excitation states (single inelastic 2_1^+ and mutual inelastic ($2_1^+, 2_1^+$) exit-channels) have been deduced by measuring their particle- γ angular correlations with Eurogam Phase II. Three quantization axes have been defined as follows : a) corresponds to the beam axis, b) axis normal to the scattering plane, and c) axis perpendicular to the a) and b) axes. The fragment detectors are placed symmetrical with respect to the beam axis and their centers are located at angles $\theta_{\text{lab.}} \simeq 45^\circ$, then the c) axis can be approximatively considered as the molecular axis parallel to the relative vector between the two centers of

the out-going binary fragments. In Fig.4 the results of the γ -ray angular correlations for the mutual excitation exit-channel are shown. The minima observed in a) and b) at 90° imply that the intrinsic spin vectors of the 2^+ states lie in the reaction plane and are perpendicular to the orbital angular momentum. So the value of the angular momentum remains close to $L = 38 \hbar$ for the two exit channels, in agreement with Fig.3. The maximum around 90° in c) suggests that the ^{28}Si spin vectors are parallel to the fragment directions with opposite directions. Such disalignments of the fragment spins are, of course, not usual in deep inelastic processes [19], but a very long life-time of the resonance might allow large microscopic fluctuations. Fig.5 displays theoretical analyses for the normal-mode motions by the molecular model [8], where the panel B) is found to have an extreme concentration of the probabilities into channel spin of $I = 0$. In $^{28}\text{Si} + ^{28}\text{Si}$ (oblate-oblate), the system would be dominated by *butterfly motion* [8,9] and the theoretical results support the *spin disalignments*. This is in contrast with the observed alignment for the prolate-prolate system $^{24}\text{Mg} + ^{24}\text{Mg}$ [14].

The feedings of the ^{28}Si states are measured in two angular regions (see Fig.3). The first is the resonance region ($73.2^\circ \leq \theta_{c.m.} \leq 105.6^\circ$ angular range) and the second is the direct-like region ($56.8^\circ \leq \theta_{c.m.} \leq 67.6^\circ$ angular range). Fig.6 shows the comparison between the experimental feedings (diamonds and triangles) for states in ^{28}Si populated in the resonance region and the theoretical feedings (histograms) predicted by TSM. We can remark that TSM does not reproduce well the experimental data feeding of the $0_1^+(\text{K}^\pi = 0_1^+)$, $2_1^+(\text{K}^\pi = 0_1^+)$, $4_3^+(\text{K}^\pi = 0_3^+)$ and $4_1^-(\text{K}^\pi = 3_1^-)$ states of ^{28}Si . The disagreement between experimental data and model calculations for the feeding of the 0_1^+ and 2_1^+ states of ^{28}Si ground band is expected to be due to resonant effects. But the disagreement for the feeding of the $4_3^+(\text{K}^\pi = 0_3^+)$ and $4_1^-(\text{K}^\pi = 3_1^-)$ states is less evident to explain. Is that linked to the resonant structure? This might be true since these states do not appear in the direct-like region.

One of the more interesting results in the $\text{K}^\pi = 0_1^+$ band is that the mutually excited states are more fed than the singly excited states $(0_1^+, 0_1^+)$, $(2_1^+, 0_1^+)$ and $(4_1^+, 0_1^+)$ (see Fig.6 : triangles) and the relative ratio (extracted by fragment-fragment- γ measurement) between them are equal to 13 %. The experimental comparison of the feeding of ^{28}Si states

between the resonance and direct-like regions is illustrated by Fig.6 and Fig.7. The feeding of $K^\pi = 3_1^-$ band is stronger than for the $K^\pi = 3_1^+$ band. The strong feeding of the $K^\pi = 3_1^-$ is approximatively the same in the resonance region and direct-like region. Finally a quantitative comparison is summarized in table 1. Where the relative total feeding of K^π bands are defined as follows :

$$\mathcal{R}(K^\pi) = \frac{\mathcal{A}(K^\pi)}{\mathcal{A}(K^\pi = 0_1^+)} \quad (2)$$

where $\mathcal{A}(K^\pi)$ is the total feeding of a K^π bands of the ^{28}Si .

The strong feeding of the $K^\pi = 3_1^-$ and $K^\pi = 0_1^+$ bands implies that ^{28}Si is dominated by oblate deformation. The more unexpected result of the comparison is that of the $K^\pi = 0_3^+$ corresponding to the large prolate deformation [15] is more fed in the resonance region than in the direct-like region by a factor 6.

B - Coincidence measurement for $^{32}\text{S} + ^{24}\text{Mg}$ exit channel

Fig.8 shows the excitation energy spectrum measured for the $^{32}\text{S} + ^{24}\text{Mg}$ exit-channel. Pronounced structures, are observed at high excitation-energy. Since the number of possible mutual excitations becomes very large above 11 MeV in this channel, the good agreement between experimental data (points) and TSM calculations (curves) for excitation-energy spectrum (see Fig.8) at low energy implies that the reaction does not proceed via resonant effects in this exit-channel. This confirms the lack of resonant structures in excitation functions for the $^{28}\text{Si} + ^{28}\text{Si} \rightarrow ^{32}\text{S} + ^{24}\text{Mg}$ channel. The disagreement between the experimental data and the TSM calculations at high excitation-energy has been investigated by looking at the γ -ray spectra of the ^{24}Mg and ^{32}S nuclei with a gate on the excitation-energy ($E_X > 10$ MeV). It is shown that the γ transitions corresponding to the ^{24}Mg and ^{32}S nuclei in this region $E_X > 10$ MeV can be formed by the mutual states in a very complicated manner that the TSM model cannot take into account due to a lack of knowledge about the experimental states at very high E_X .

The study of the $^{32}\text{S} + ^{24}\text{Mg}$ exit channel using fragment-fragment coincidences has

been supported by the fragment-fragment- γ measurement. The γ -rays associated to ^{32}S and ^{24}Mg have been established [12]. The γ -ray spectrum of ^{24}Mg shows more γ -ray transitions between positive parity states and also the appearance of the high excitation-energy 6_1^+ (8.11 MeV) and 6_2^+ (9.53 MeV) states. In summary, the desexcitation of the ^{24}Mg nucleus during its rotation seems to feed the first rotational bands $K^\pi = 0^+$ and $K^\pi = 2^+$, which correspond to the prolate deformation.

A more unexpected result for $^{32}\text{S} + ^{24}\text{Mg}$ exit-channel arises from the spectroscopic study of the ^{32}S nucleus (see Fig.9). According to the branching ratios of the $1_3^- \rightarrow 2_1^+$ arising to the ^{32}S desexcitation, which have been given by Rogers and al. [16], there is an indication from our data of a signature of a new γ -ray transition,

$$0^+(8507.8 \text{ keV}) \rightarrow 2_1^+(2230.2 \text{ keV})$$

We can remark from the inspection of the γ -ray spectrum of ^{32}S , as shown in the Fig.9, a strong feeding of the negative parity states with lower spins. These states have been selectively excited in the α transfer reaction such as $^{28}\text{Si}(^6\text{Li}, d)^{32}\text{S}$ [17] and $^{28}\text{Si}(^{16}\text{O}, ^{12}\text{C})^{32}\text{S}$ [18].

IV. SUMMARY AND CONCLUSIONS

A high-resolution study of fragment-fragment- γ data collected with the Eurogam Phase II multi-detector array for the $^{28}\text{Si} + ^{28}\text{Si}$ reaction at bombarding energy $E_{\text{lab.}} = 111.6$ MeV has allowed us to extract very attractive and new results.

In the $^{28}\text{Si} + ^{28}\text{Si}$ exit-channel, the resonant behavior of the $^{28}\text{Si} + ^{28}\text{Si}$ exit-channel is clearly observed by the present fragment-fragment coincidence data. The more unexpected result is the spin disalignment of the $^{28}\text{Si} + ^{28}\text{Si}$ resonance. This has been demonstrated first by the measured angular distributions of the elastic, inelastic, and mutual excitation channels, which are dominated by a unique and pure partial wave with $L = 38 \hbar$, and has been confirmed by measuring their particle- γ angular correlations with Eurogam Phase II. The disalignment is supported by molecular model predictions, in which the state with the butterfly mode is expected to correspond to the observed resonance. The study of the feeding of bands of ^{28}Si , has revealed that $K^\pi = 0_3^+$ corresponding to the large prolate deformation is more fed in the resonance region than in the direct-like region. The good agreement between data and TSM (fusion-fission model) calculations suggests the importance of the fission decay at high-excitation energy while the resonant behavior involves the low-lying states.

In the $^{32}\text{S} + ^{24}\text{Mg}$ exit-channel, the spectroscopic study of the ^{32}S nucleus, has revealed the contribution of a new γ transition $0^+(8507.8 \text{ keV}) \rightarrow 2_1^+(2230.2 \text{ keV})$ in the deexcitation process of ^{32}S . The γ -ray spectrum of the ^{32}S shows more γ -ray transitions between negative parity states with lower spins.

Acknowledgments : We would like to acknowledge the VIVITRON operators for providing us well focussed ^{28}Si beams.

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TABLES

K^π	5_1^-	3_1^-	0_1^+	3_1^+	0_3^+	0_2^+
Kind of deformation [15]	large oblate deformation	oblate deformation	oblate deformation	prolate deformation	large prolate deformation	prolate deformation
$\mathcal{R}(K^\pi)$ resonance region	2.1 %	8.2 %	100 %	4.4 %	5.8 %	1.2 %
$\mathcal{R}(K^\pi)$ direct-like region	0.7 %	6.7 %	100 %	4.5 %	1.1 %	1.3 %

TABLE I. *Relative total feeding of K^π bands ($\mathcal{R}(K^\pi)$) for states in ^{28}Si populated in the resonance and in the direct-like regions.*

FIGURE CAPTIONS

Fig.1 : Two-dimensional energy spectrum E_4 versus E_3 of the fragments detected by one pair of position-sensitive Si detectors for the $^{28}\text{Si} + ^{28}\text{Si}$ reaction at $E_{lab.} = 111.6$ MeV.

Fig.2 : Excitation-energy spectra for $^{28}\text{Si} + ^{28}\text{Si}$ exit-channel. The points are the efficiency corrected experimental data. The curves are TSM calculations for fission decay to particle-bound states (solid curve) and for all decays (dotted curve).

Fig.3 : Experimental angular distributions of the elastic, inelastic 2_1^+ and mutual excitation ($2_1^+, 2_1^+$), excitation channels. The solid lines are calculated distributions based on a $[P_L(\cos \theta_{c.m.})]^2$ angular dependence.

Fig.4 : Experimental γ -ray angular correlations of the ($2_1^+, 2_1^+$) states in the resonance region $73.2^\circ \leq \theta_{c.m.} (^{28}\text{Si}) \leq 105.6^\circ$ of the $^{28}\text{Si} + ^{28}\text{Si}$ exit channel for three quantization axes.

Fig.5 : Molecular model prediction for Probability distributions of the $^{28}\text{Si} + ^{28}\text{Si}$ ($[2_1^+ \otimes 2_1^+]$ with $L = J - I$) system versus channel spin I (see ref. [9]).

Fig.6 : Comparaision between experimental feeding (diamonds and triangles) for states in ^{28}Si populated in the resonance region and calculated feedings predicted by TSM (histograms) for a statistical FF process.

Fig.7 : Experimental feeding (diamonds) for states in ^{28}Si populated in the direct-like region.

Fig.8 : Excitation-energy spectra for $^{32}\text{S} + ^{24}\text{Mg}$ exit-channel. The points are the efficiency corrected experimental data. The curves are TSM calculations for fission decay to particle-bound states (solid curve) and for all decays (dotted curve).

Fig.9 : γ -ray spectrum in coincidence with ^{32}S for the $^{28}\text{Si} + ^{28}\text{Si}$ reaction at resonance energy $E_{lab} = 111.6$ MeV.